Search for Doubly-charged Higgs Boson Production in the Decay $H^{++}H^{--} \to \mu^+\mu^+\mu^-\mu^-$ with the DØ Detector at $\sqrt{s} = 1.96$ TeV

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ABSTRACT

A search for the pair production of doubly-charged Higgs bosons in the process $p\overline{p} \to H^{++}H^{--} \to \mu^+\mu^+\mu^-\mu^-$ is performed with the DØ Run II detector at the Fermilab Tevatron using inclusive di-muon events. These data taken at an energy of $\sqrt{s} = 1.96$ TeV correspond to an integrated luminosity of 113 pb^{-1} and were recorded by DØ between August 2002 and June 2003. In the absence of a signal, 95% Confidence Level mass limits of $M(H_L^{\pm\pm}) > 118.6$ GeV and $M(H_R^{\pm\pm}) > 98.1$ GeV are set on the pair production cross section for left-handed and right-handed doubly-charged Higgs bosons, assuming 100% branching into muons and hypercharge $|Y| = 2$.

1   Theory

Doubly-charged Higgs bosons appear in left-right symmetric models, in Higgs triplet models [1] and in little Higgs models [2]. The dominant decay modes are expected to be like-sign lepton pairs, $H^{\pm\pm} \to \ell^\pm\ell^\pm$. Decay modes with mixed lepton flavor are also possible. In most models, the $H^{\pm\pm}$ coupling to W pairs is suppressed due to the requirement that the vacuum expectation value of the neutral member of the Higgs multiplet vanishes. This is needed to constrain the ρ parameter to unity at tree level.

Pairs of doubly-charged Higgs bosons are produced through the Drell-Yan process $q\overline{q} \to \gamma^*/Z \to H^{++}H^{--}$. Next-to-leading (NLO) order corrections to this

cross section have recently been calculated [3]. The pair production cross sections for left-handed states in the mass range studied in this analysis are about a factor two larger than for the right-handed states due to different coupling to the intermediate Z boson. Left-handed and right-handed states are distinguished by their decays into left-handed or right-handed leptons. The cross section also depends on the hypercharge Y of the $H^{\pm\pm}$ boson.

LEP experiments have searched for pair production of doubly-charged Higgs Bosons in e^+e^- scattering. Mass limits of $M(H_{\rm L}^{\pm\pm}) > 100.5\,{\rm GeV}$ and $M(H_{\rm R}^{\pm\pm}) > 100.1\,{\rm GeV}$ were obtained by OPAL [4], and a limit of $M(H_{{\rm L}(R)}^{\pm\pm}) > 99.4\,{\rm GeV}$ by L3 [5] for decays into muons. All limits in this Letter are given at 95% Confidence Level (C.L.) and for a branching of 100%. Similar mass limits were set for decays into electrons [4, 5] or τ-leptons [4, 5, 6].

The analysis [7] is based on inclusive di-muon data taken between August 2002 and June 2003. The total integrated luminosity for the accepted di-muon triggers is determined to be $113 \pm 7\,{\rm pb}^{-1}$.

2 Event selection

The event selection is performed in four steps. The first step (selection S1) requires at least two muons, each with transverse momenta $p_T > 15\,{\rm GeV}$, where p_T is measured with respect to the beam axis. In the second selection (S2), isolation criteria based on calorimeter and tracking information are applied to reject background mainly from muons originating from semi-leptonic b quark decays. The next selection (S3) requires that for events with exactly two muons the difference in azimuthal angle $\Delta\phi$ is less than $4\pi/5$. It is applied to reject $Z \to \mu^+\mu^-$ events where one of the charges is mismeasured and to further reduce semi-leptonic b decays. This also removes any remaining small background from cosmic muons. In the final selection (S4) at least one pair of muons in the event is required to be of like-sign charge. These pairs are considered candidates for $H^{\pm\pm} \to \mu^\pm\mu^\pm$ decays.

When the requirement of having at least one pair of like-sign muons is applied at the same time as the selection S1, most of the background from Z decays is removed, and only 101 like-sign events remain (Table 1). Since no isolation is imposed at this stage, the most probable background is due to $b\bar{b}$ production.

PYTHIA is used to estimate this background by generating inclusive jet events with a minimum transverse momentum for the hard interaction of 30 GeV [8]. The inclusive b quark production cross section $\sigma^b(p_T^b > 30\,{\rm GeV})$ was measured by DØ to be (54 ± 20) nb in the rapidity interval $|y^b| < 1$ at $\sqrt{s} = 1.8$ TeV [9]. This

Table 1: Expected number of background events from Monte Carlo, and number of data events remaining after each selection cut.

Selection (like-sign)	2 muons $p_T > 15$ GeV	Isolation	$\Delta\phi < 4\pi/5$
	S4 & S1	S2	S3
$Z \to \mu^+\mu^-$	0.9 ± 0.3	0.6 ± 0.2	0.3 ± 0.1
$b\overline{b}$	95.1 ± 3.3	4.4 ± 0.8	0.8 ± 0.2
$Z \to \tau^+\tau^-$	0.6 ± 0.3	< 0.3	< 0.3
$t\overline{t}$	0.24 ± 0.01	0.11 ± 0.01	0.11 ± 0.01
ZZ	0.06 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
WZ	0.29 ± 0.01	0.27 ± 0.01	0.23 ± 0.01
MC (sum)	97.2 ± 3.3	5.5 ± 0.7	1.5 ± 0.4
data	101	5	3

cross section, extrapolated to the full y^{b} range and to $\sqrt{s} = 1.96$ TeV, is used to normalize the $b\overline{b}$ MC sample.

In Fig. 1, di-muon mass and $\Delta\phi$ of the like-sign events are compared to the PYTHIA $b\overline{b}$ simulation. Data and Monte Carlo are in good agreement. Out of 101 like-sign events, 5 remain after applying the isolation requirement, while 16 events remain after applying only the $\Delta\phi$ requirement. Assuming that all like-sign events originate from $b\overline{b}$ processes, the isolation and $\Delta\phi$ selection efficiencies for $b\overline{b}$ events are 5% and 16%, respectively. Using these the background from $b\overline{b}$ production in the final sample is expected to be 0.8 ± 0.2 events.

Another potential background are $Z \to \mu^+\mu^-$ decays where one of the muon charges is misidentified. We have therefore measured the charge misidentification probability in data. 0.45 background events are expected due to charge misidentification. This is in good agreement with 0.3 ± 0.1 events expected from Monte Carlo. Three candidates remain in the data after the final selection.

3   Limit Calculation and Systematic Uncertainties

The limit calculations are performed using the program MCLIMIT [10]. It provides the confidence level for the background hypothesis, CL_B, and the confidence level for the signal with background hypothesis, CL_{S+B}, taking into account the expected mass distribution for the signal and for the background, and the mass resolution [11]. The expected signal rate as a function of the Higgs mass is given by the NLO cross
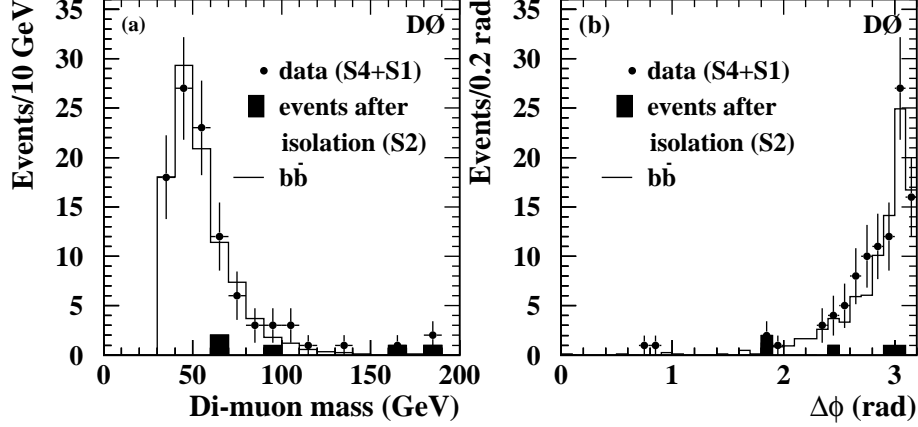
Figure 1: (a) Di-muon mass and (b) $\Delta\phi$ distributions for the 101 like-sign events remaining in data after the selections S1 and S4 (points with error bars), compared to the PYTHIA $b\bar{b}$ simulation (histogram). The five events remaining after the isolation selection are shown separately.

section [3], the signal efficiencies, and the measured luminosity.

The 95% C.L. limit is determined from the confidence level of the signal $CL_S = CL_{S+B}/CL_B$ by requiring $CL_S = 0.05$[1].

The following sources of systematic uncertainty affecting the normalization of the signal are taken into account: The systematic uncertainty on the luminosity obtained using the DØ luminosity system is estimated to be 6.5%. The total uncertainty on the efficiency amounts to 5%.

The theoretical uncertainty on the NLO $H^{\pm\pm}$ production cross section from choice of parton distribution function and variations of the renormalization and factorization scales is about 10% [3].

The statistical uncertainty on the MC background rate is 27% (Table 1). Adding the systematic uncertainty of 25% on the measured $b\bar{b}$ cross section [9] yields a total uncertainty on the background rate of 50%.

4   Results

Taking into account the systematic uncertainties, a lower mass limit of 118.6 GeV is obtained for a left-handed and a mass limit of 98.1 GeV for a right-handed doubly-charged Higgs boson, assuming 100% branching into muons, hypercharge $Y = |2|$,

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[1]By definition the hypothesis of having a signal plus background is excluded at the 95% C.L. if $CL_{S+B} < 0.05$.
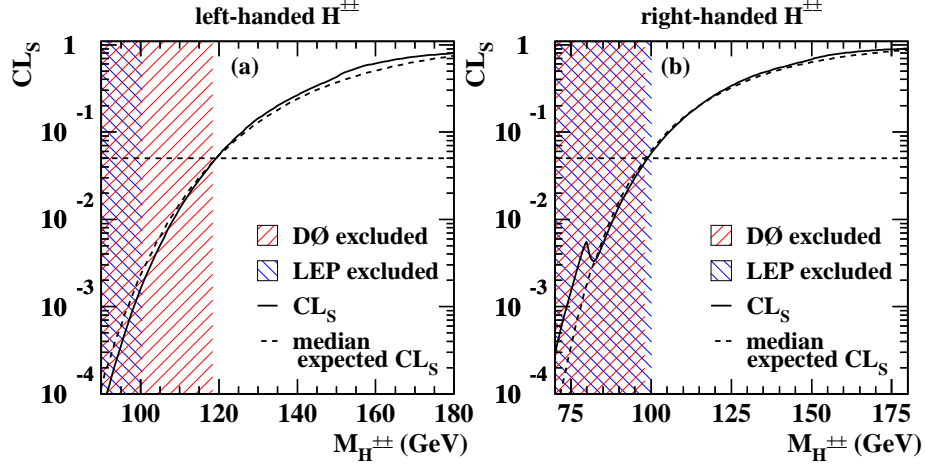
Figure 2: Confidence level of the signal, $CL_S = CL_{S+B}/CL_B$, as a function of the mass $M(H^{\pm\pm})$ of (a) left-handed and (b) right-handed doubly-charged Higgs bosons. The mass regions $M(H_L^{\pm\pm}) < 100.5$ GeV and $M(H_R^{\pm\pm}) < 100.1$ GeV are excluded by LEP. The impact of systematic uncertainties is included in the limits. The dashed curve shows median expected CL_S for no signal.

and Yukawa couplings $h_{\mu\mu} > 10^{-7}$. This significantly extends the previous mass limit of 100.5 GeV for a left-handed doubly-charged Higgs boson [4].

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